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REVIEW

New Light on Dark Matter

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Dark matter, proposed decades ago as a speculative component of the universe, is now known to be the vital ingredient in the cosmos: six times more abundant than ordinary matter, one-quarter of the total energy density, and the component that has controlled the growth of structure in the universe. Its nature remains a mystery, but assuming that it is composed of weakly interacting subatomic particles, is consistent with large-scale cosmic structure. However, recent analyses of structure on galactic and subgalactic scales have suggested discrepancies and stimulated numerous alternative proposals. We discuss how studies of the density, demography, history, and environment of smaller-scale structures may distinguish among these possibilities and shed new light on the nature of dark matter.

The dark side of the universe first became evident about 65 years ago when Fritz Zwicky (*1*) noticed that the speed of galaxies in large clusters is much too great to keep them gravitationally bound together unless they weigh over 100 times more than one would estimate on the basis of the number of stars in the cluster. Decades of investigation confirmed his analysis (*2–5*), and by the 1980s, the evidence for dark matter with an abundance of about 20% of the total energy density of the universe was accepted, although the nature of the dark matter remained a mystery.

After the introduction of inflationary theory (*6*), many cosmologists became convinced that the universe must be flat and that the total energy density must equal the value (termed the critical value) that distinguishes a positively curved, closed universe from a negatively curved, open universe. Cosmologists became attracted to the beguiling simplicity of a universe in which virtually all of the energy density consists of some form of matter, about 4% being ordinary matter and 96% dark matter. In fact, observational studies were never really compliant with this vision. Although there was a wide dispersion in total mass density estimates, there never developed any convincing evidence that there was sufficient matter to reach the critical value. The discrepancy between observation and the favored theoretical model became increasingly sharp.

Dark energy came to the rescue when it was realized that there was not sufficient matter to explain the structure and nature of the universe (*7*). The only thing dark energy has in common with dark matter is that both components neither emit nor absorb light. On a microscopic scale, they are composed of different constituents. Most important, dark matter, like ordinary matter, is gravitationally self-attractive and clusters with ordinary matter to form galaxies. Dark energy is gravitationally self-repulsive and remains nearly uniformly spread throughout the universe. Hence, a census of the energy contained in galaxies would miss most the dark energy. So, by positing the existence of a dark energy component, it became possible to account for the 70 to 80% discrepancy between the measured mass density and the critical energy density predicted by inflation (*8–11*). Then, two independent groups (*12*, *13*) found evidence of the accelerated expansion of the universe from observations of supernovae, and the model with a dominant dark energy component, as illustrated in Fig. 1, became the concordance model of cosmology. The existence of dark energy has recently been independently confirmed by observations by the Wilkinson Microwave Anisotrope Probe [WMAP (*14*)] and has become accepted as an essential ingredient of the standard model (*15*).

Dark energy has changed our view of the role of dark matter in the universe. According to

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Einstein's general theory of relativity, in a universe composed only of matter, it is the mass density that determines the geometry, the history, and the future of the universe. With the addition of dark energy, the story is different. First, what determines the geometry of the universe is whether the total energy density equals the critical value, where now we add to the mass contribution (identifying its energy according to $E = mc^2$) the dark energy contribution. Second, the period of matter domination has given way to dark energy domination. So, the important role of dark matter is in the past, when it was the dominant contribution to the energy density; roughly the first few billion years. Our future is determined by the nature of the dark energy, which is sufficient to cause the current expansion of the universe to accelerate, and the acceleration will continue unless the dark energy should decay or change its equation of state.

We have neglected one very important subplot up to this point: dark matter as the agent producing the growth of cosmic structure. We would not exist today were it not for dark matter, which played a crucial role in the formation of the present structure in the universe. Without dark matter, the universe would have remained too uniform to form the galaxies, stars, and planets. The universe, although nearly homogeneous and isotropic on its largest scales, shows a bewildering variety of structures on smaller scales: Stars, galaxies, clusters of galaxies, voids, and great walls of galaxies have been found. The only known force capable of moving matter on such large scales is Newton's gravity. And because, in a smooth and uniform medium, there will be no irregularities to produce gravitational forces, all structures must have been seeded by small fluctuations imprinted on the universe at very early times. These fluctuations should leave a signature on the cosmic background radiation (CBR) left over from the Big Bang. Ordinary matter could not produce fluctuations to create any substantial structures without leaving a signal bigger than what was observed in the CBR, because it remained tightly coupled to radiation, preventing it from clustering, until recent epochs.

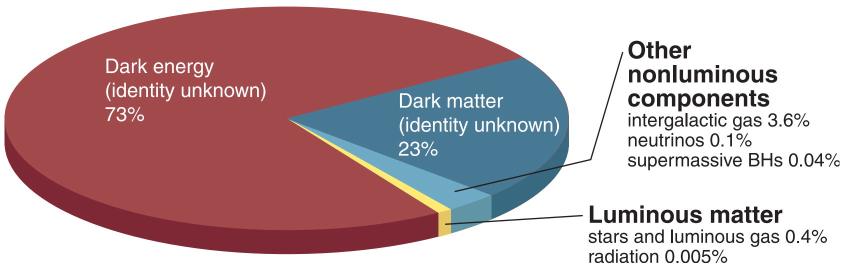

Fig. 1. The luminous (light-emitting) components of the universe only comprise about 0.4% of the total energy. The remaining components are dark. Of those, roughly 3.7% are identified: cold gas and dust, neutrinos, and black holes. Nearly 23% is dark matter, and the overwhelming majority is some type of gravitationally self-repulsive dark energy.

On the other hand, dark matter, which is not coupled to photons, would permit tiny fluctuations (consistent with the CBR observations) to grow for a long, long time before the ordinary matter decoupled from radiation. Then, the ordinary matter would be rapidly drawn to the dense clumps of dark matter and form the observed structures. There would still need to be initial fluctuations, but their amplitude could be substantially smaller than otherwise. The required material was called cold dark matter, because it consisted of nonrelativistic particles that were assumed to contain no internal thermal motions (that is, they were cold).

A final important ingredient in the standard paradigm must be mentioned before we can begin to assess the validity of the picture. The initial spectrum of perturbations (the ratio of long waves to short waves) must be specified in order to predict the gravitational effects of these waves. The initial density fluctuations were scale-invariant. That is, if we decomposed the energy distribution into a sum of sinusoidal waves of varying wavelengths, the wave amplitudes of the waves were the same for all wavelengths. One of the great triumphs of the inflationary scenario (*16–20*) is that it provided a well-motivated dynamical mechanism for producing a nearly scale-invariant (defined by spectral index $n = 1$) spectrum. This prediction has now been confirmed by the WMAP, which found $n = 0.99 \pm 0.04$ (*21*).

But we cannot claim to understand the the universe if we do not know the nature of dark matter. Two kinds of dark matter are already known, neutrinos and black holes (*22*), but they are thought to make minor contributions to the total. The majority component remains unknown. Here we explore these issues: the possible candidates, their implications for structure formation, and how we might use a combination of particle detectors and astronomical observations to resolve the nature of dark matter.

The Favored Candidates for Dark Matter

For over a decade, the favored candidates for dark matter have been hypothetical elementary particles that are long-lived, cold, and collisionless. Long-lived means the lifetime must be comparable to or greater than the present age of the universe, about 14 billion years. Cold means that the particles are nonrelativistic at the onset of the matter-dominated epoch, so that they are immediately able to cluster gravitationally. Because clustering occurs on length scales smaller than the Hubble horizon (the age of the universe multiplied by the speed of light), and the Hubble horizon was much smaller during the era of matter domination than today, the first objects to form—clumps or halos of dark matter—were much smaller and less massive than the Milky Way. As the universe expanded and the Hubble horizon grew, many of these first small halos merged to form larger-scale structures, which later merged to form yet larger-scale structures. The result is a hierarchy of structure ranging over many orders of magnitude in volume and mass, which is qualitatively in accordance with what is observed. In contrast, hot relativistic particles, such as light massive neutrinos, would be moving too fast during the time of matter domination to cluster gravitationally, and would result in a distribution of structure that is inconsistent with what is observed. Hence, light neutrinos must be a negligible component of the dark matter mass density, a conclusion supported by measurements of the neutrino mass in underground solar neutrino experiments. Collisionless means that the interaction cross-section between dark matter particles (and between dark matter and ordinary matter) is so small as to be negligible for densities found in dark matter halos. The particles are only gravitationally bound to one another and travel unimpeded in orbits in the halos with a broad spectrum of eccentricities.

Cold collisionless dark matter (CCDM) has been favored for several reasons. First, numerical simulations of structure formation with CCDM agree with most observations of structure. Second, for a special subclass known as WIMPs (weakly interacting massive particles), there is a natural explanation for why they have the requisite abundance. If particles interact through the weak force, then they were in thermal equilibrium in the first trillionths of a second after the Big Bang, when the density and temperature were high. Then they fell out of equilibrium, with a concentration that is predicted from their annihilation cross-section. For a weak force cross-section, the expected mass density today spans a range that includes 20 to 30% of the total energy density of the universe, as observed. A third reason for favoring CCDM is that there are specific appealing candidates for the particles in models.

One candidate is the neutralino, a particle that arises in models with supersymmetry. Supersymmetry, a fundamental aspect of supergravity and superstring theories, requires a (yet unobserved) boson partner particle for every known fermion and a fermion partner particle for every known boson. If supersymmetry were extant today, the partners would have the same mass. But because supersymmetry would have been spontaneously broken at high temperatures in the early universe, today the masses are different. Also, most supersymmetric partners are unstable and decayed soon after the breaking of symmetry. However, there is a lightest partner (with mass on the order of 100 GeV) that is prevented by its symmetries from decaying. In the simplest models, these particles are electrically neutral and weakly interacting—ideal candidates for WIMPs. If the dark matter consists of neutralinos, then underground detectors can detect their passage through Earth as the planet travels around the Sun and through the dark matter in the solar neighborhood. However, it is important to note that detection alone does not necessarily mean that dark matter consists primarily of WIMPS. The current experiments cannot determine whether WIMPS are a majority or, like neutrinos, a small minority of the dark matter.

Another appealing candidate is the axion, a very light neutral particle (with mass on the order of 1 μeV) that is important in suppressing strong CP violation in unified theories. The axion interacts through such a tiny force that it is never in thermal equilibrium, so the explanation for its abundance is not as simple. It immediately forms a cold Bose condensate that permeates the universe. Axion detectors have been constructed and the search for them is under way.

Cracks in the Foundation

Because the standard model, combined with CCDM, is mathematically quite specific (even if some of the parameters that enter into it are imprecisely known), it can be tested at many different scales. The largest scales (thousands of megaparsecs) are seen in the CBR. CBR measurements show the primordial distribution of energy and matter when their distribution was nearly uniform and there was no structure. Next come measurements of the large-scale structure seen in the distribution of galaxies ranging from several Mpc to nearly 1000 Mpc. Over these scales, observation and theory are consistent, inspiring great confidence in the overall picture.

However, on smaller scales, from 1 Mpc down to the scale of galaxies, kiloparsecs, and below, there is inconsistency. These apparent disagreements began to surface several years ago (*23–25*), and no consensus has emerged as to whether they represent real problems. For the most part, theorists believe that, if there is a problem, it is much more likely to be due to our specific assumptions about the nature of dark matter than to a problem with the global picture given by the standard model. That there should be more uncertainty about smaller objects that are relatively closer may seem puzzling at first, but there are natural explanations. First, on large scales gravity is dominant, so an understanding of the predictions involves only computations based on Newton's and Einstein's laws of gravity. On smaller scales, the complex hydrodynamical interactions of hot dense matter must be included. Second, the fluctuations on large scales are small and we have accurate methods of computing such quantities. But on the scales of galaxies, the physical interactions of ordinary matter and radiation are more complex. The principal purported problems found on smaller scales are as follows: Substructure—small halos and galaxies orbiting within larger units—may not be as common as expected on the basis of numerical simulations of CCDM. The number of halos expected varies roughly as the inverse of the mass, so many more dwarf galaxy systems should have been observed. The lensing effect of small halos should be evident from the distribution of brightnesses of multiple images of a given galaxy, but the current evidence is inconclusive (*26*). The small halos, spiraling into the Milky Way and other systems, should puff up the thin disks of normal galaxies to a greater degree than is observed (*27*, *28*)

The density profile of dark matter halos should exhibit a cuspy core in which the density rises sharply as the distance from the center decreases, in contrast to the central regions of many observed self-gravitating systems. Clusters of galaxies, as observed in studies of gravitational lensing, have less cuspy cores than do computed models of massive dark matter halos (*29*). Ordinary spiral galaxies have much less dark matter in their inner parts than expected (*30*, *31*), as do some low-surface-brightness galactic systems (*32*). Dwarf galaxies, like our companion systems Sculptor and Draco, have nearly uniform-density cores in contrast to the expected cuspy density profile (*33*, *34*). Hydrodynamic simulations produce galaxy disks that are too small and have too little angular momentum as compared to observations (*35*). Many high-surface-brightness spiral galaxies exhibit rotating bars, which are normally stable only if the core density is lower than predicted (*36*).

It is conceivable that the resolution of the growing list of problems lies in complex but more ordinary astrophysical processes. Numerous ingenious but conventional explanations for the absence of substructure have been proposed (*37–39*). The second set of objections, based on the cuspy density profile expected for CCDM, is observationally stronger, but here it may be that the theoretical predictions of a cuspy profile are not as certain as had been supposed (*40–42*). Overall, however, the evidence to date, taken in its totality, does indicate a discrepancy between the predicted high densities and the observed much lower densities in the inner parts of dark matter halos, ranging from those in giant clusters of galaxies [mass (M) $\geq 10^{15}$ solar masses ($M_\odot$)] to those in the smallest dwarf systems observed ($M \leq 10^9\ M_\odot$).

Alternatives to Cold Dark Matter

The possible discrepancies between theory and observation have motivated new proposals about the nature of dark matter. Each proposed variation from CCDM has two properties: (i) it can solve some or all of the problems described in the previous section, and (ii) it leads to additional predictions that would distinguish it from all the other alternatives. We discuss the following possible alternative models of dark matter.

1) Strongly self-interacting dark matter (SIDM). The dark matter might have a significant self-scattering cross-section σ, comparable to the nucleon-nucleon scattering cross-section (*43*). Then in any halo, large or small, where the number of particles per unit area (the surface density) × σ is greater than unity, collisions among the dark matter particles lead to a complex evolution of the structure. During the initial phase of this process, which lasts longer than the present age of the universe, the central densities decline in the desired fashion because of the scattering of dark matter particles. Also, scattering strips the halos from small clumps of dark matter orbiting larger structures, making them vulnerable to tidal stripping and reducing their number.

2) Warm dark matter (WDM). Dark matter may be born with a small velocity dispersion (for example, through decay of another species) (*44*, *45*), which leaves it with a velocity of perhaps only 100 m/s. Extrapolating back in time, this velocity increases to a value sufficient to have a significant effect on small-scale structure, because the particles are moving too fast to cluster on these scales. There are fewer low-mass halos, and all halos have a less steep profile in the innermost core. Also, because most of the lowest-mass halos are born from the fragmentation of larger structures in this picture, they are found in high-density regions, and the voids tend to be emptier of small systems than in the CCDM scenario.

3) Repulsive dark matter (RDM). Dark matter may consist of a condensate of massive bosons with a short-range repulsive potential (*46*). The inner parts of dark matter halos would behave like a superfluid and be less cuspy.

4) Fuzzy dark matter (FDM). Dark matter could take the form of ultralight scalar particles whose Compton wavelength (effective size) is the size of a galaxy core (*47*). Therefore, the dark matter cannot be concentrated on smaller scales, resulting in softer cores and smaller-scale structure.

5) Self-annihilating dark matter (SADM).

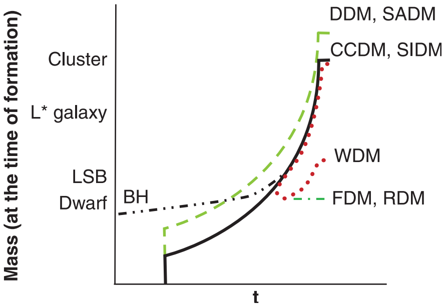

Fig. 2. History of structure formation: the time of formation for objects of a given mass (as measured at formation) for structures with increasing mass [dwarf galaxies, low-surface-brightness (LSB) galaxies, ordinary (L*) galaxies, and galaxy clusters] for different models of dark matter. Structure formation begins shortly after the onset of the matter-dominated epoch (left side).

Dark matter particles in dense regions may collide and annihilate, liberating radiation (*48*). This reduces the density in the central regions of clusters by direct removal of particles from the center and by the reexpansion of the remainder as the cluster adjusts to the reduced central gravity.

6) Decaying dark matter (DDM). If early dense halos decay into relativistic particles and lower mass remnants, then core densities, which form early, are reduced without altering large-scale structure (*49*).

7) Massive black holes (BH). If the bulk of the dark matter in galactic halos were in the form of massive black holes with masses of about one million $M_{\odot}$, then several dynamical mysteries concerning the properties of our galaxy could be better understood (*50*). In normal galaxies, dynamical friction between the massive black holes and the ordinary matter would cause the black holes in the central few kiloparsecs to spiral into the center, depleting those regions of dark matter and providing the ubiquitous central massive black holes seen in normal galaxies.

Determining the Nature of Dark Matter

At first sight, the conceivable alternatives to CCDM are so numerous that it may seem impossible ever to distinguish among them. However, each alternative produces distinctive modifications on small scales that can be tested through improved astronomical observations and numerical simulations. The local universe—the small objects that orbit galaxies and the galaxy cores—turns out to be a marvelous laboratory for examining the nature of dark matter.

SIDM, BH, or SADM only affect halos when the interaction rate rises above a certain threshold value. The interaction rate depends on the surface density if the cross-section is velocity-independent or, more generally, is the product of the cross-section and velocity. In all these cases, the interaction effect is slow because only a few scatterings take place within the lifetime of the universe. WDM, RDM, or FDM have a built-in characteristic length scale below which dark matter halos are affected. DDM has a characteristic built-in time scale after which dark matter halos are affected on all length scales and for all surface densities.

The alternatives also alter the history of structure formation compared to CCDM in different ways. SIDM maintains the same sequence of structure formation but slowly rearranges the distribution of dark matter in dense regions. SADM is similar, except that it removes dark matter altogether from dense regions. Depending on details, RDM and FDM may or may not affect the sequence of structure formation either, but they ensure that the smaller-scale objects are forced to have a low density. DDM removes dark matter on all scales beginning after a characteristic decay time; because a lot of mass is lost through the decays, a higher rate of clustering is required throughout to match the observed galaxy cluster masses and match the other proposals. WDM delays the onset of structure formation until the dark matter cools sufficiently to gravitationally cluster, initially suppressing small-scale structure formation but then creating it later by the fragmentation of larger-scale structures. Finally, the BH alternative requires that significant nonlinear structure on one million $M_{\odot}$ scales be built in ab initio, rather than grown from small fluctuations.

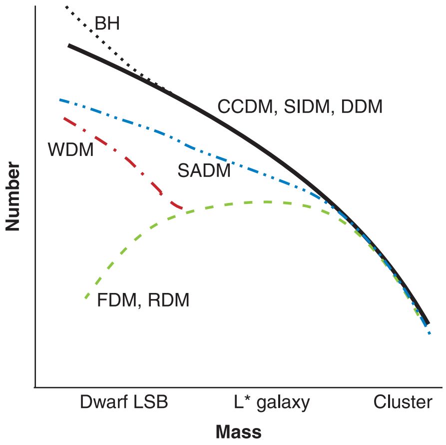

Fig. 3. Demography: how the number of objects of a given type depends on their mass (as observed today) for different dark matter models.

Because of these differences, the candidates for dark matter each face distinctive constraints and challenges. If the cross-section is too large, self-interaction or self-annihilation could lead to the evaporation of the halos of galaxies in clusters, which is in conflict with observations (*31*, *51*). For WDM, for which structure formation is delayed as compared to the standard picture, evidence for early galaxy and star formation provides a strong constraint. If the high electron-scattering optical depth found by WMAP is confirmed (an indicator of substantial star formation at very early epochs), there would not be room for any delay (*21*, *52*). Similarly, SADM could destroy all small halos made at early times before they become sites for new small galaxies. A challenge for DDM is that it requires a higher production of massive dense clusters in the early universe than has been observed in order to obtain the right mass distribution after decay.

We suggest that new kinds of observations may be able to distinguish among the candidates for dark matter by taking advantage of their qualitative differences. To be quantitative in our predictions, detailed numerical simulations of each case are necessary. It may be that some of the guesses we are putting forward will turn out to be incorrect when accurate calculations are made.

First we consider the epoch at which objects of different mass will form in the different scenarios (Fig. 2). To give the same structures today, objects of a given mass will need to form earlier in the DDM, SADM, and BH scenarios as compared to the standard CCDM and SIDM scenarios. The low-mass objects will form later in at least some FDM and RDM scenarios, and in the WDM scenario, they will form later and only from the fragmentation of more massive objects. The mass of, and even the existence of, low-mass galaxies at early times will provide a valuable diagnostic to distinguish among the alternatives.

Next we look at the demography: that is, how many small and large dark matter halos are expected in the local universe when population studies are completed (Fig. 3). In the

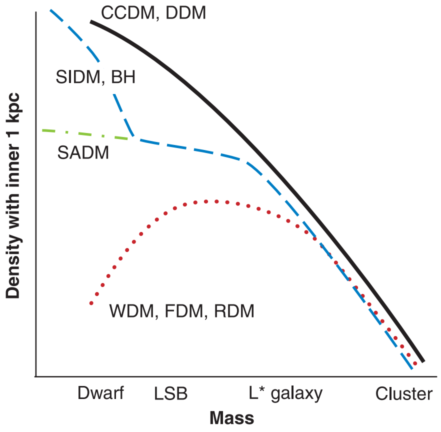

Fig. 4. Internal structure: how the density of the inner 1 kpc depends on the mass of the system for different dark matter models.

WDM, FDM, and RDM scenarios, low-mass objects are underabundant as compared to the CCDM, SIDM,and SADM scenarios; and in the BH scenario, they are probably overabundant. WDM calculations (*45*) reveal that objects made by fragmentation are present but at a lower level. The small halos may be difficult to observe directly, because they may be unable to retain gas long enough to make observable galaxies. But these small dark halos may be detected through their gravitational effects, such as lensing, puffing up of disks, and other dynamical interactions.

The internal structure of the halos provides another feature to distinguish one model from another. In the CCDM model, low-mass halos were made early when the universe was denser, and so they are more dense than structures formed later. This is shown in their internal structure. So, Fig. 4 reflects the historical conditions shown in Fig. 2 but allows one to study nearby objects. This is a critical issue because the inner parts of dark matter halos do seem to be considerably less dense than expected in the CCDM model. Here the BH scenario is complex. For isolated dark matter halos, which do not contain ordinary matter, the dynamical evolution will be qualitatively similar to that of star clusters. On a time scale proportional to the dynamical (or orbital) time multiplied by the ratio of the system mass to the typical black hole mass, the inner profile will first flatten and then collapse via a process called the gravothermal instability. For parameters appropriate to galactic dark matter halos, even the first process will only occur for the lowest-mass dwarf systems, and thus less cuspy cores would be expected in the local dwarf galaxies. In normal galaxies, the stronger interaction is between the black holes and the normal stellar component, and this leads, as noted before, to clearing out the black holes from the inner parts of the galaxies, with them sinking to the center where they either merge or are ejected.

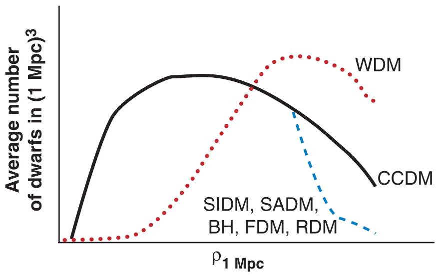

Fig. 5. Environment: how the number of dwarfs in a (1 Mpc)^3 volume depends on the average density within that volume.

Finally, in Fig. 5, we examine the environments within which different kinds of objects should be found. In the CCDM model, low-mass halos will be distributed relatively more uniformly than will the higher-mass halos, so that the large voids seen in the distribution of massive galaxies should be populated with halos of low mass and perhaps also with associated low-mass galaxies. To date, studies have not found such galaxies, but we do not yet know if this because of an absence of the predicted low-mass halos in the voids or simply because the ones that are there have not been able to make galaxies. In the WDM scenario, the low-mass halos are typically near the high-mass ones, because they form from the fragmentation of larger structures. For the SIDM, SADM, FDM, and RDM scenarios, the abundance of low-mass objects will decline in the vicinity of the highest-mass ones. In SIDM, it will be because interactions will boil away the cooler low-mass halos by direct particle-particle collisions, and in the other three cases, it is because the low-mass halos will have a low internal density and be fragile, hence easily shredded in tidal encounters with their bigger brothers. For the BH scenario, the voids would be heavily populated with small dark matter systems, but these might or might not contain observable stellar systems.

Conclusions

There are a variety of clues telling us that the universe may not be as simple as the CCDM model. Although the CCDM model is able to correctly predict observations made on the largest cosmological scales down to roughly those of galactic scale, and from the early universe to the present epoch, there are many indications that on subgalactic scales it predicts that there should be more dark matter than is detected gravitationally. Numerical simulations predict that all galaxies should contain cuspy cores, where the density of dark matter rises sharply with decreasing radius, and most observations do not confirm this prediction. We need more accurate simulations and more accurate observations to see whether these discrepancies are real. If they are, then there are several interesting suggestions that could account for the less cuspy cores and, more important, would lead to predictions of other observables that could be used to test the variant types of dark matter. These include the history of dark halo formation, the demography (mass distribution) of low-mass halos, the detailed interior density distribution of galaxy halos, and the environments within which different kinds of astronomical objects are found. We have sketched out the kinds of astronomical tests that could be done to narrow the search, but if history teaches us anything it is that the next important clues will come from a surprising direction. Some observation or calculation will be made that will reorient our inquiries and, if this happens as has happened so often in the past, we will realize that the important evidence has been sitting unnoticed under our noses for decades.

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